VALIDATION OF NECK INJURY CRITERIA USING RECONSTRUCTED REAL-LIFE REAR-END CRASHES WITH RECORDED CRASH PULSES

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ABSTRACT

To date no AIS1 neck injury mechanism has been established, thus no neck injury criterion has been validated against such mechanism. Validation methods not related to an injury mechanism may be used. The aim of this paper was to validate different proposed neck injury criteria with reconstructed real-life crashes with recorded crash pulses and with known injury outcomes.

A car fleet of more than 40,000 cars fitted with crash pulse recorders have been monitored in Sweden since 1996. All crashes with these cars, irrespective of repair cost and injury outcome have been reported. With the inclusion criteria of the three most represented car models, single rear-end crashes with a recorded crash pulse, and front seat occupants with no previous long-term AIS1 neck injury, 79 crashes with 110 front seat occupants remained to be analysed in this study. Madymo models of a BioRID II dummy in the three different car seats were exposed to the recorded crash pulses. The dummy readings were correlated to the real-life injury outcome, divided into duration of AIS1 neck injury symptoms. Effectiveness to predict neck injury was assessed for the criteria NIC, N_{km}, NDC and lower neck moment, aimed at predicting AIS1 neck injury. Also risk curves were assessed for the effective criteria as well as for impact severity.

It was found that NIC_{max} and N_{km} are applicable to predict risk of AIS1 neck injury when using a BioRID dummy. It is suggested that both BioRID NIC_{max} and N_{km} should be considered in rear-impact test evaluation. Furthermore, lower neck moment was found to be less applicable. Using the BioRID dummy NDC was also found less applicable.

INTRODUCTION

The safety level of cars has improved considerably the latest years, especially regarding the risk of severe injury (Kullgren et al. 2002). The safety regarding disabling injuries has also improved. However, the most common example, disability due to a neck injury classified as AIS1, has increased in terms of number and risk since the early 80's (Krafft 1998, Kullgren et al. 2002). Most occupants reporting an AIS1 neck injury recover, often within a month while 5-10% sustain permanent disability (Nygren 1984, Gustavsson et al 1985, Galasko et al. 1996). Although a small percentage and a low AIS scoring (AIS1), the disability caused by these injuries corresponds to the major part of the societal cost and individual suffering resulting from car crashes (Krafft 1998, Hell et al. 1998). It is important that test methods and tools to evaluate the risk of these injuries are developed.

Several studies have shown correlation between risk to sustain an AIS1 neck injury and impact severity (Krafft 1998, Krafft et al. 2001). Among evaluated severity parameters, car acceleration levels in the impact phase seems to well correlate with the risk to sustain an injury. Based on data from crash recorders, average acceleration levels for occupants with initial whiplash symptoms and more long-term symptoms have been presented (Krafft et al. 2001). The risk to sustain a long-term injury was approaching 100% at a car mean acceleration above 7 g, while for a car mean acceleration below 4g it was zeroing. Such information is useful in designing test specifications, and it is important to further analyse injury risks in rear impacts.

For frontal and side impact situations there are legislation and consumer tests with standardised crash test dummies, the HIII and Euro/US-SID, as well as AIS3+ neck injury criteria, the upper neck forces and moments (Mertz, 1984) or combinations thereof (Kleinberger et al. 1998). For rear impact situations there are no legislation tests nor commonly accepted AIS1 neck injury criteria. Nevertheless, two rear impact crash test dummies have recently been developed, the Biofidelic Rear Impact Dummy (BioRID) by a Swedish consortium (Davidsson et al 1998) and the Rear Impact Dummy version2 (RID2) by TNO (Cappon et al, 2000). The BioRID, a completely new dummy with fully articulated spine (24 pin joints) was developed to mimic volunteer kinematics. The RID2 is a modification kit (articulated spine and improved back shape) for the

50th percentile HIII dummy. Both dummies have been shown to be more biofidelic in rear impact testing compared with the HIII dummy (Davidsson et al. 1999, Siegmund et al. 2001, Philippens et al. 2002). Also, various AIS1 neck injury criteria have been proposed the latest ten years, for example, NIC (Boström et al. 1996), N_{km} (Schmitt et al, 2002), lower neck moment (Prasad et al. 1997) and NDC (Viano and Davidsson, 2001). The NIC considers the relative horizontal acceleration and velocity between the bottom (T1) and the top (C1) of the cervical spine. The Nkm is a combination of upper neck shear and flexion/extension moment. The NDC is based on the angular and linear displacement response of the head relative to T1. Of these criteria, NIC have been evaluated most thoroughly and have been shown to be sensitive, in a real-life like manner, to seat structure characteristics, head-to-headrest distance and crash pulse (see for example Bostrom et al 1996, Bostrom et al 1997, Bostrom et al 1998, Eichberger et al 1998, Kleinberger 2000, Eichberger 2000, Bostrom et al 2000, Eriksson and Bostrom 2002, Hell et al, 2002). When it comes to evaluation of a large set of parameters such as crash pulse or head-to-headrest distance, an effective alternative to mechanical simulations is mathematical simulations. Eriksson and Bostrom (2002) showed a BioRID I Madymo model (Eriksson 2000) to be an effective tool in crash reconstruction analysis.

To achieve a situation with cost-effective rear-impact protection-systems in all cars, effective test methods must be established. A countermeasure evaluation method normally includes a crash test dummy, crash pulses and criteria. For a method to be effective, the method must reflect real life crash situations. A somewhat unique issue regarding rear-impact test validation or relevance to real-life crashes is the lack of well established AIS1 neck injury mechanisms and precise diagnosis. A strategy, used in this study, to overcome the involvement of injury mechanisms and diagnosis, is to correlate/validate simulated AIS1 neck injury criteria to neck injury outcome sustained by occupants exposed for well documented real-life crashes.

The aim of this paper was to validate different proposed neck injury criteria with reconstructed real-life crashes with recorded crash pulses and with known injury outcomes. Symptom duration of 110 occupants (whereof 13 sustained injuries lasting more than one month) were compared with mathematical (MADYMO) simulations with a BioRID II dummy.

MATERIAL AND METHODS

Real-world data

A data set consisting of real-life rear-end impacts was used as input for computer simulations. Since 1996 Folksam Insurance Company in Sweden have fitted a car fleet of more than 40,000 cars, consisting of 7 models of the same make, with crash pulse recorders aimed at measuring acceleration-time history in rear-end impacts. All crashes with these cars, irrespective of repair cost and injury outcome have been reported. With the inclusion criteria of the three most represented car models, single rear-end crashes with a recorded crash pulse, and front seat occupants with no previous long-term AIS1 neck injury, 79 crashes with 110 front seat occupants remained to be analysed in this study.

The crash pulse recorder records the acceleration-time history with a sampling frequency of 1000 Hz in the impact phase of a crash. Acceleration was measured in the principle direction of force within +/- 30 degrees. Crash pulses were filtered at approximately 60 Hz. Change of velocity and mean and peak accelerations were calculated from the recorded crash pulses. Mean acceleration was calculated during the main part of the pulse until the acceleration approached zero. The threshold of the recorder is approximately 3 g.

The occupant injury status was divided in categories regarding duration of symptoms; no, initial and symptoms more than one month. Injury status was established from telephone interviews. For those occupants reporting a whiplash injury, follow-ups of medical symptoms were made at several occasions, however at least ones after 6 months. Examples of symptoms are neck pain, headache, dizziness, and neck stiffness. The numbers of occupants in the three included car models are presented in Table 1 for the various injury categories.

The age distribution and gender for the injury categories can be seen in Table 2. It was a similar proportion of males and females for occupants with symptoms more than one month and for all occupants. Also average age was similar for those groups. Occupants that reported an AIS1 neck injury but recovered within a month had lower average age and higher proportion of females compared to the other injury categories, see Table 2.

Table 1. Number of occupants in various car models

	Total			Car model 1		Car model 2		Car model 3	
	Total	D	FSP	D	FSP	D	FSP	D	FSP
No neck injury	67	50	17	16	5	20	10	14	2
Initial symptoms	30	20	10	3	3	13	6	4	1
Symptoms > 1 month	13	9	4	3	1	3	2	3	1
Total	110	79	31	22	9	36	18	21	4

D = Driver, FSP = Front Seat Passenger

Table 2. Gender and average age for occupants with various injury categories

	Average age	Gender (%)	
		Male	Female
No neck injury	46.8	53	47
Initial symptoms	39.4	32	68
Symptoms > 1 month	47.4	46	54
Total	45.0	47	53

Simulation model

Three seat models were built up in Madymo since the seats in the three analyzed car models differed in geometry and stiffness characteristic. The geometries of the mechanical seats were measured and the cushion, the seat-back, and the head restraint contours were implemented into Madymo in order to achieve correct contact areas between the seats and the dummy. Also, parts of the seat structures that may influence on the dummy kinematics during the crashes were implemented. For each seat model two mechanical crash tests with the BioRID II were carried out at Δv 23 km/h and mean acceleration 4.5 g. The BioRID II was seated in a normal posture and no seat belts were used. The initial seat back inclination in the mechanical tests corresponded to a torso angle at 25° on an H-point mannequin and the head restraints were placed in their lowest positions. The spread in the dummy responses within similar seats were used to establish corridors for the x- and z-accelerations in the dummy head, C4, T1, T8, L1, and pelvis, for the y-rotations of the dummy head, T1, and pelvis, for the seat inclinations and deformations, and for the dummy upper neck loads. The stiffness characteristics of the Madymo seat models were then tuned with the aim to fit the responses from the Madymo models into the mechanical test response corridors. Differences between the seats that influenced on the dummy kinematics were seat-back height and stiffness characteristic, head restraint position and stiffness characteristic, recliner stiffness characteristic, and geometry of the upper seat-back structure.

All analyzed crashes were reconstructed in Madymo by exposing the Madymo seat models and a Madymo model of the BioRID II to the recorded crash pulses. The Madymo BioRID II (release date Feb. 27 2002) used was an upgrade of the Madymo BioRID I (Eriksson, 2002). The Madymo BioRID II were placed in a normal posture, no seat belts were used, and the head restraints were placed in their lowest position with the exception of the seat with the lowest seat-back where the head restraint was placed 30 mm upward from its lowest position. For all crashes the NIC_{max} (Bostrom et al. 2000, however filtered at CFC180), N_{km} (Schmitt et al. 2002), lower neck moment (Prasad et al. 1997) and NDC (Viano and Davidsson 2001) were calculated. The BioRID II accelerations and upper neck loads were filtered according to Davidsson (1999) for the mechanical tests and no filter was used for the Madymo simulations.

Correlation analysis

Injury risk was evaluated by calculating the ratio of injured occupants and all occupants in intervals of impact severity or intervals of each neck injury criterion. Injury risk was calculated for each injury severity level. Smooth curve fits (see software KaleidaGraph 2000) were used to visualise changes in risk for increasing impact severity or injury criterion. No risk functions were calculated.

To further study how impact severity influenced injury outcome, and to study how parameters were correlated, the parameters were plotted versus each other for the three injury severity levels included. Also simulated neck injury criteria were plotted versus measured impact severity.

A new criterion, MIX, based on N_{km} and NIC_{max} was calculated as Eq 1, where NIC_{av} is the average NIC_{max} and N_{av} is the average N_{km} in this sample.

$$MIX = SQRT((NIC_{max}/NIC_{av})^2+(N_{km}/N_{av})^2) \quad (Eq\ 1)$$

An attempt was also made to statistically show how well the injury criteria explain the risk of sustaining symptoms for more than 1 month. As a global assessment of the effectiveness for each criterion to predict an injury ROC curves (Receiver Operating Characteristic) were calculated (Bland 2000), where sensitivity was plotted against 1-specificity. The area under the curve (AUC) was compared to the null hypothesis of a 0.5 level for uninformative tests. For a maximum effective criteria the area should be 1.00. A 95% confidence interval was calculated for each area.

Two sets of thresholds were chosen corresponding to a sensitivity of 77% (10 occupants out of 13 with symptoms more than one month) and 92% (12/13). For each threshold specificity and positive and negative predictive values were calculated. The definition of the statistical terms were (according to Bland (2000));

- Sensitivity – the proportion of injured occupants above the chosen threshold
- Specificity – the proportion of uninjured occupants below the threshold.
- Positive predictive value – the proportion of all occupants above threshold that were injured.
- Negative predictive value – the proportion of all occupants below threshold that were uninjured.

Note that the sensitivity measures how good the criterion is at finding an injured occupant and the specificity to excluding an uninjured. The positive predictive value is the probability that an occupant above a threshold is injured. The negative predictive value is the probability that an occupant below a threshold is uninjured. 95% confidence intervals were calculated for the positive and negative predictive values.

To evaluate correlation between NDC and injury outcome, vertical versus horizontal displacements and angular versus horizontal displacement were studied. According to Viano and Davidsson (2001) occupants outside boundary lines are exposed to higher risk. Due to the current definition of NDC, no statistical analyses or risk curves could be made to compare NDC with the other injury criteria.

RESULTS

In the real-life data sample the average change of velocity was 10.0 km/h and the average mean acceleration 3.5 g. The maximum change of velocity was 33.2 km/h and the maximum mean acceleration was 10.2 g. This can be seen in Figure 1 and 2 presenting the number of observations in intervals of

change of velocity and mean acceleration. The maximum peak acceleration was 21.7 g.
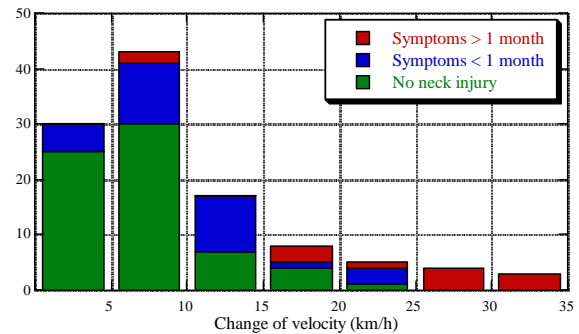

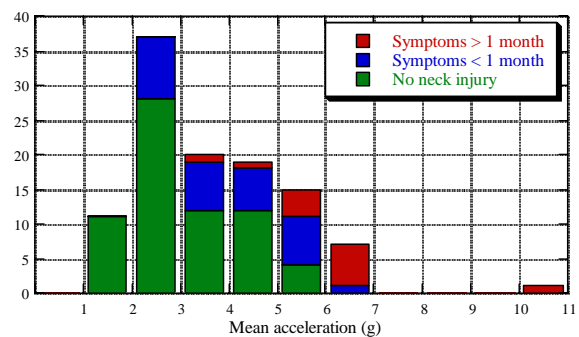**Figure 1. Number of crashes in intervals of change of velocity.**

Figure 2. Number of crashes in intervals of mean acceleration.

A correlation can be seen for risk of both initial symptoms and for symptoms lasting longer than one month for all three impact severity parameters included, see Figures 3, 4 and 5. The risk of symptoms more than one month was low at change of velocity below 15 km/h, and at a mean acceleration below 5 g and at a peak acceleration below 10 g. Between 5 and 7 g the risk of symptoms more than one month increased from almost 0% to almost 100%, see Figure 4.
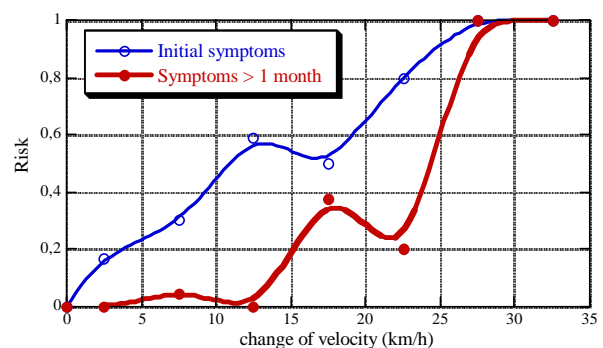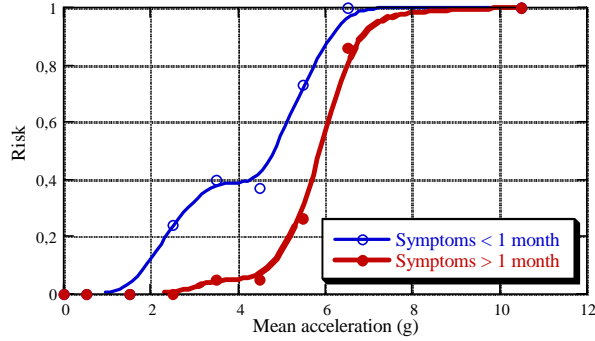

Figure 3. Injury risk versus change of velocity.

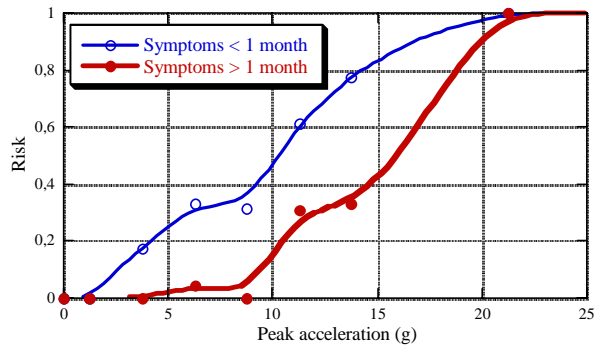**Figure 4. Injury risk versus mean acceleration.**

Figure 5. Injury risk versus peak acceleration

To study how change of velocity, mean and peak acceleration together influences the injury risk, Figures 6 and 7 can be studied. Below 3 g in mean acceleration no occupant with symptoms more than one month have been found and only one out of 13 of these occupants had a mean acceleration below 4.5 g. Similarly, only one out of these 13 occupants had a peak acceleration below 10 g, see Figure 7.
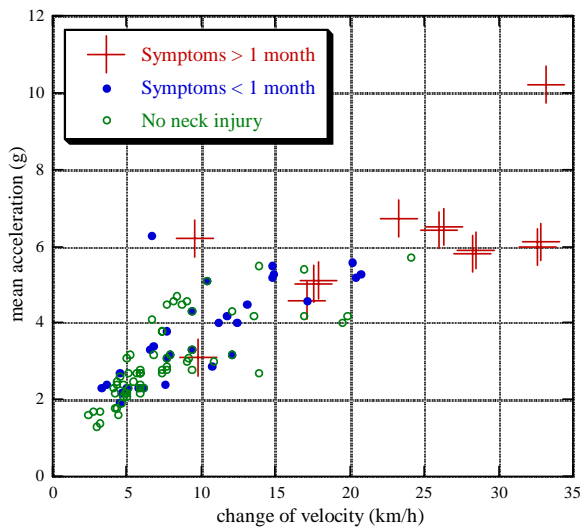

Figure 6. Change of velocity and mean acceleration for occupants in different injury categories.
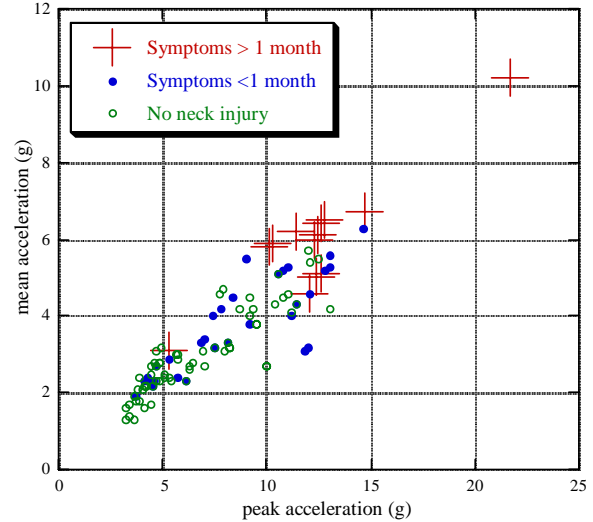

Figure 7. Peak and mean accelerations for occupants in different injury categories.

In the following three plots, Figures 8, 9 and 10, NIC_{max}, N_{km} and lower neck moment are plotted against mean acceleration to visualise how these correlate with injury outcome. Only one occupant with symptoms for more than one month had a NIC_{max} below 15 m^2/s^2, see Figure 8. One of the occupants with a NIC_{max} above 15 m^2/s^2 had low mean acceleration close to 3 g, see Figure 8. The same crash can also be seen in Figure 9, where the corresponding N_{km} was 0.4. It was also found that most of the occupants with symptoms more than one month, 11 out of 13, also had N_{km} above 0.98.
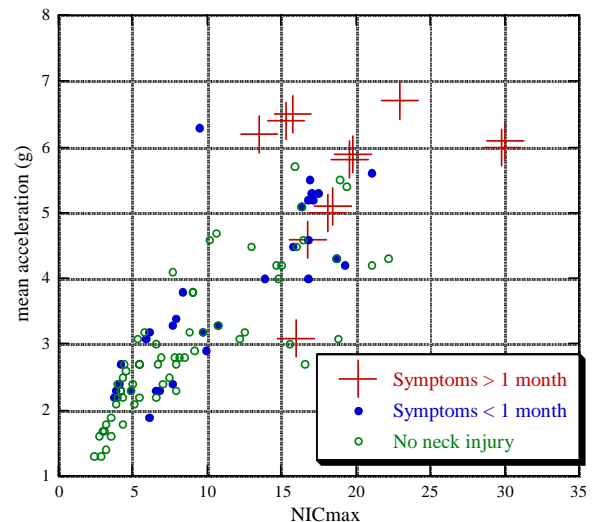

Figure 8. NIC_{max} and mean acceleration for occupants in different injury categories (the occupant with a NIC_{max} of 55.5 m^2/s^2 was excluded in the plot).
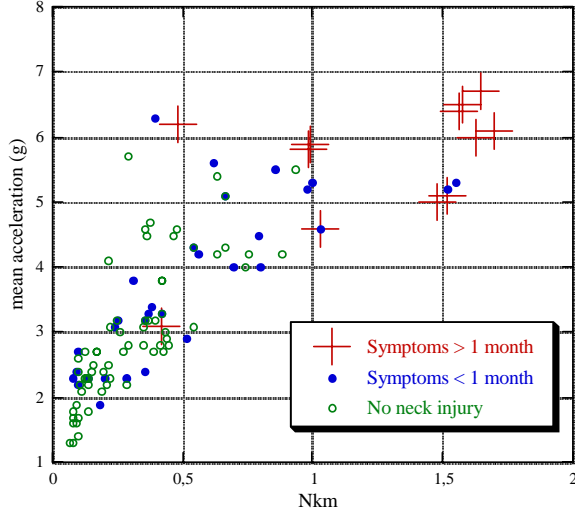
Figure 9. N_{km} and mean acceleration for occupants in different injury categories (the occupant with a N_{km} of 3.0 was excluded in the plot).
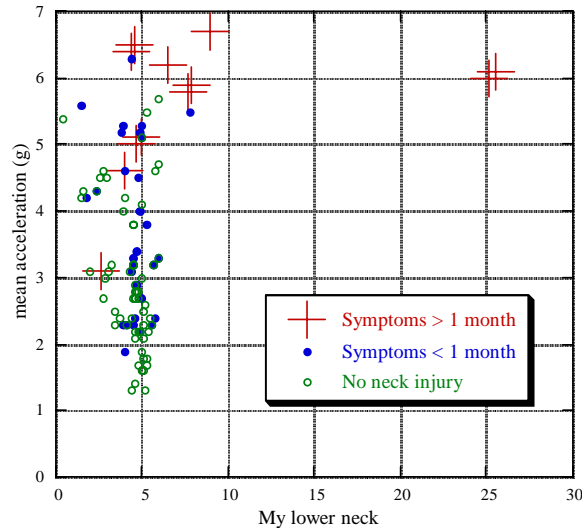

Figure 10. Lower neck moment and mean acceleration for occupants in different injury categories (the occupants with moment above 30 Nm were excluded in the plot).

The correlation between NIC_{max} and N_{km} is shown in Figure 11. At a given NIC_{max} a large variation in N_{km} was found, see Figure 11. At a NIC_{max} of 16 m^2/s^2 N_{km} varied from 0.4 to 1.6. The result indicates that you may sustain a neck injury with long-term symptoms at both high NIC_{max} and high N_{km}.
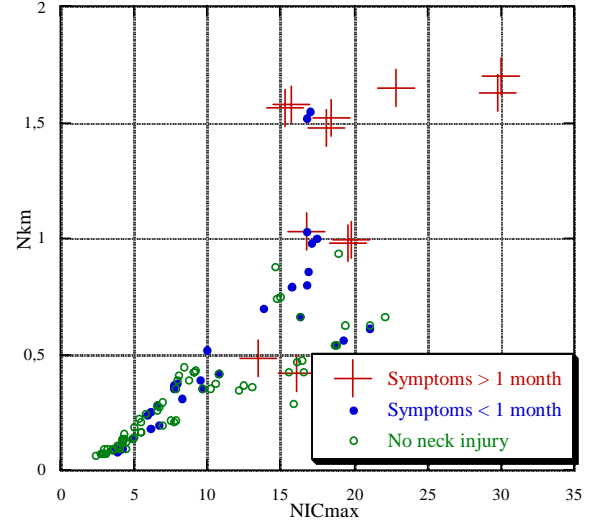

Figure 11. NIC_{max} and N_{km} for occupants in different injury categories (the occupant with a NIC_{max} of 55.5 m^2/s^2 and a N_{km} of 3.0 was excluded in the plot

According to the AUC calculation it was found that all criteria were significantly above the 0.5 level for uninformative tests showing that all criteria can be used to predict a neck injury with symptoms more than one month. It can be seen in Table 3 showing the areas below the ROC-curves (AUC) presented in Figure 12. However, no conclusive difference was found for the criteria, except from MIX in comparison with lower neck moment, see Table 3. Concerning initial symptoms all criteria were significantly above the 0.5 level for uninformative tests except the lower neck moment, which did not pass the test. Therefore, all criteria except the lower neck moment can also be used to predict a neck injury with initial symptoms.
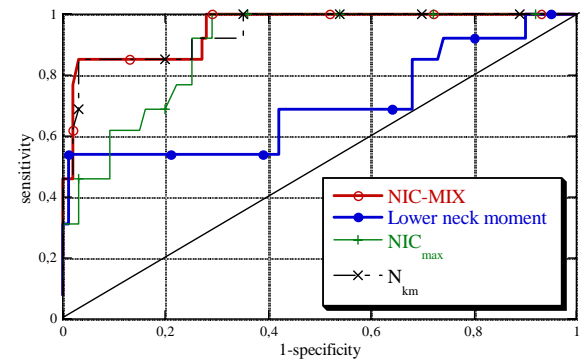

Figure 12. ROC-curves for NIC_{max}, N_{km}, MIX and lower neck moment (occupants with symptoms more than one month).

Table 3. AUC for occupants with initial symptoms or symptoms more than one month

	Injury criterion	AUC	Std error	P-values	95% confidence interval	
					Lower bound	Upper bound
Occupants with symptoms more than one month	NIC_{max}	0.893	(0.035)	0.000	0.824	0.963
	N_{km}	0.944	(0.032)	0.000	0.882	1.000
	MIX	0.950	(0.029)	0.000	0.893	1.000
	My	0.702	(0.095)	0.018	0.515	0.889
Occupants with initial symptoms	NIC_{max}	0.737	(0.048)	0.000	0.642	0.832
	N_{km}	0.776	(0.047)	0.000	0.684	0.868
	MIX	0.768	(0.058)	0.000	0.676	0.860
	My	0.564	(0.058)	0.257	0.451	0.677

Table 4. Positive and negative predictive values for occupants with symptoms more than one month

Injury criterion	Threshold*	$P_{specificity}$	Proportion of occupants **with** symptoms > 1 month above threshold (Positive Predictive Value)	Proportion of occupants **not** having symptoms > 1 month below threshold (Negative Predictive Value)
	P_{sens} = 0.77			
NICmax	16.04	0.80	10/29 = **34%** ± 17%	78/81 = **96%** ± 4%
N_{km}	0.9815	0.97	10/13 = **77%** ± 23%	94/97 = **97%** ± 3%
My	4.34	0.32	10/76 = **13%** ± 8%	31/34 = **91%** ± 10%
MIX	3.80	0.98	10/12 = **83%** ± 21%	95/98 = **97%** ± 3%
	P_{sens} = 0.92			
NICmax	15.30	0.75	12/36 = **33%** ± 15%	73/74 = **99%** ± 2%
N_{km}	0.4809	0.75	12/36 = **33%** ± 15%	73/74 = **99%** ± 2%
My	3.97	0.26	12/84 = **14%** ± 7%	25/26 = **96%** ± 8%
MIX	2.32	0.73	12/38 = **32%** ± 15%	71/72 = **99%** ± 2%

*Thresholds were chosen as the levels for each injury criterion where the proportions of occupants with symptoms > 1 month where 10/13 and 12/13. This means that the sensitivities chosen were 0.77 and 0.92 respectively.

Table 5. Positive and negative predictive values for occupants with initial symptoms

Injury criterion	Threshold**	$P_{specificity}$	Proportion of occupants **with** initial symptoms above threshold (Positive Predictive Value)	Proportion of occupants with **no** neck injury below threshold (Negative Predictive Value)
	P_{sens} = 0.79			
NICmax	7.67	0.54	34/65 = **52%** ± 12%	36/45 = **80%** ± 12%
N_{km}	0.2805	0.54	35/66 = **53%** ± 12%	36/44 = **82%** ± 11%
My	3.97	0.27	35/84 = **42%** ± 11%	18/26 = **69%** ± 18%
MIX	1.17	0.54	35/66 = **53%** ± 12%	36/44 = **82%** ± 11%

**Threshold was chosen as the level for each injury criterion where the proportion of occupants with initial symptoms where 35/43. This means that the sensitivity chosen was 0.79%.

To further study the usefulness of the included neck injury criteria, the proportion of occupants with initial symptoms or symptoms more than one month above and below a threshold for each injury criteria was studied, see Table 4 and 5. At a sensitivity of 0.92, which corresponds to a NIC_{max}-threshold of 15.3 m^2/s^2 and a N_{km}-threshold of 0.48, the probability that an occupant is injured and correctly classified as injured was 33% ± 15% for both criteria. The probability that an occupant is uninjured and correctly classified as uninjured was 97-100% for both N_{km} and NIC_{max}, see Table 4. At a sensitivity of 0.77, the probability that an occupant is injured and correctly classified as injured was 34% ± 17% for NIC_{max}, 77% ± 23% for N_{km} and 83% ± 21% for MIX. The probability that an occupant is uninjured and correctly classified as uninjured at the sensitivity of 0.77 was between 94% and 100% for N_{km} and MIX, and between 92% and 100% for NIC_{max}. The lower neck moment showed lower predictive values for all sensitivity levels. No significant differences in predictive values were found between the injury criteria predicting initial symptoms, see Table 5.

Figures 13 to 16 show neck injury risk for the various neck injury criteria. At a NIC_{max} of approximately 15 m^2/s^2 the risk of symptoms for more than one month was 20%, see Figure 13. For N_{km} the corresponding value was 0.8, see Figure 14, for lower neck moment 5 Nm, see Figure 15, and for MIX 3.2, see Figure 16.

No clear correlation between NDC and injury outcome could be found, see Figures 17 and 18. Occupants with symptoms more than one month were found to have similar combinations of horizontal and both vertical and angular displacements as the occupants without symptoms more than one month.
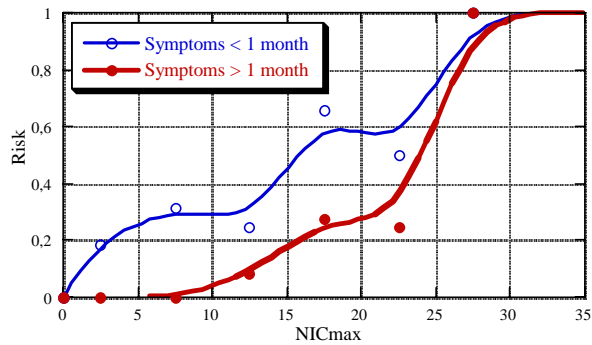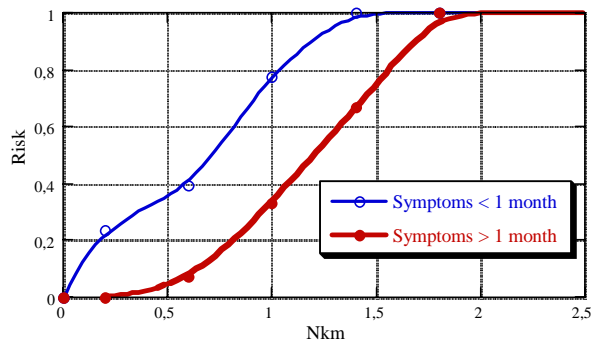

Figure 16. Neck injury risk versus MIX.
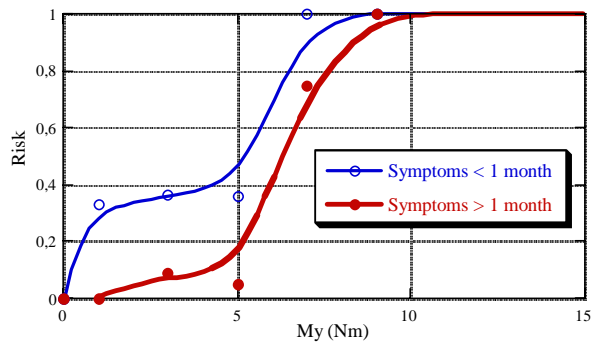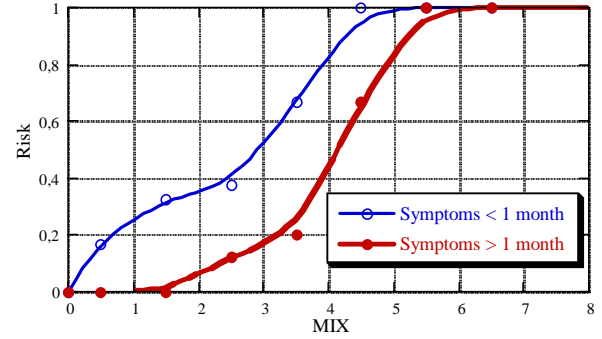

Figure 13. Neck injury risk versus NIC_{max}.

Figure 17. NDC, vertical versus horizontal displacements for different neck injury categories.

Figure 14. Neck injury risk versus N_{km}.

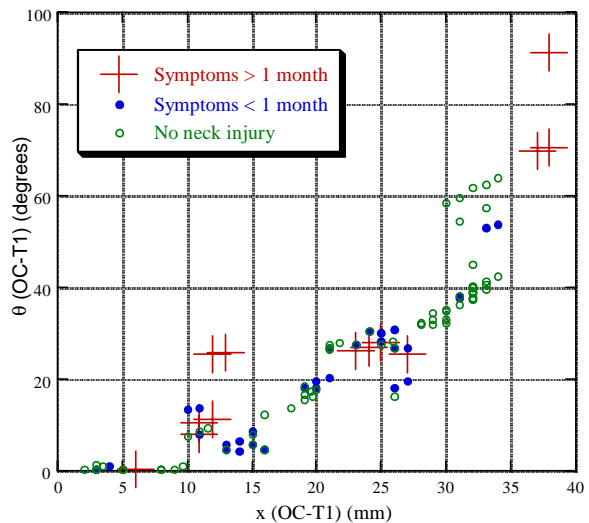**Figure 15. Neck injury risk versus lower neck moment.**

Figure 18. NDC, rear bending versus horizontal displacements for different neck injury categories.

DISCUSSION

Although the mechanisms causing the AIS1 neck injuries are not fully known, it is possible to identify parameters influencing the injury risk. Studies have shown that the risk to sustain an AIS1 neck injury has increased since the early 80's (Krafft 1998, Kullgren et al. 2002). Since the late 90's and more frequently in the beginning of year 2000 whiplash protection systems have been introduced on the market, see for example Wiklund and Larsson (1997), Jakobsson (1998) and Sekizuka (1998). Studies have shown positive effects of such systems (Viano and Olsén 2001, Farmer et al. 2002). If comparative crash tests with specific neck injury criteria could mirror these differences, these criteria could be useful in the development of new systems aimed at preventing neck injuries. Such comparative test could be used to validate, or study correlation with, injury criteria.

There are other methods possible to use to validate injury criteria. Crash tests with volunteers or PMHS have been used. However, if volunteer test should be used to fully validate injury criteria, tests must be performed at impact severity levels where injuries occur. In this study dummy readings from crash reconstruction were compared with real-life injury outcome, which has the advantage in the way a large variation in crash type and severity could be covered. However, such method is useful only if the data and reconstruction model used is of high quality. In this study it was clearly demonstrated that the data and validation method used are applicable.

Although self-reported injury symptoms were used, a strong correlation between duration of symptoms and both impact severity and neck injury criteria was found. If only symptoms verified by a doctor had been used, a stronger correlation could be expected.

In the real-life data, crash recorders with a trigger level of 3 g were used. Approximately 40% of all reported crashes had acceleration levels below 3 g and therefore no recorded crash pulse. This has been described by Krafft et al (2002). No occupant with symptoms more than one month was found in these crashes. If these low severity crashes would have had a recorded crash pulse and been included in the data sample, the negative predictive values would have been higher. However, the positive predictive values would most likely not be changed.

Madymo models of seats and the BioRID II were used to estimate the criteria in the analysed crashes. Seat models were developed in this study, and the seat stiffness characteristics were tuned to fit into response corridors establish from mechanical tests. However, some responses did not fit into these corridors. For all seats, the dummy accelerations fitted into the corridors before head to head restraint contact, although resulting in lower NIC_{max} values for the Madymo simulations compared to the mechanical tests. The head restraint position relative to the BioRID II head was lower for Car model 1 compared to the other seats. In the mechanical tests, that resulted in contact conditions between the head and the head restraint not likely to occur in real-life crash since the non-biofidelic lower edge of the BioRID back head hooked on the top of the head restraint. In order to avoid this hooking, the head restraint in Car model 1 was placed 30 mm above its lowest position in the reconstruction simulations.

The mechanical BioRID II neck consists of vertebrae connected by pin joints and cables acting as neck muscles substitutes. These cables are not modelled in the Madymo BioRID II, which resulted in somewhat inadequate head and neck rotations, and upper neck moments. The N_{km} values calculated in Madymo matched those measured in the mechanical test for Car model I, but were higher for Car model 2 and 3. Despite the risk of too high N_{km} values in the reconstruction simulations, the conclusions regarding N_{km} as a criterion suitable for predicting AIS1 neck injuries are likely accurate.

The only parameter that was varied in the simulations was the crash pulse and the seat. Many parameters known to influence neck injury risk, such as seat posture, head twisting, sex, psychosocial factors etc were not taken into account. Nevertheless, the NIC_{max} and the N_{km} values predicted occupants with symptoms for more than one month with high accuracy. Further studies where more parameters are known and controlled for could be expected to show higher effectiveness to predict neck injury for these criteria.

Several studies have shown correlation between risk to sustain a neck injury and impact severity (Ryan et al. 1994, Eichberger et al. 1996, Krafft et al. 2002). Especially acceleration levels in the impact phase seems to well correlate with risk to sustain an injury (Krafft et al 2002). In this study it was found that below 5 g in mean acceleration the risk to sustain a long-term neck injury seems to be very low. At mean accelerations above 7 g the risk seems to approach 100%. Furthermore, in the data set with recorded crash pulses at Folksam no one has to date been found to have symptoms for more than one month as long as the mean acceleration was below 3 g. Such

information is useful in the design of crash tests aimed at predicting AIS1 neck injuries.

Regarding the plots for NDC (Figures 17 and 18) no correlation to injury outcome could be seen. An explanation could be that NDC was developed to predict AIS1 neck injury when using the HIII dummy. Although it is necessary with further analyses, it appears unlikely that a correlation would be found if using the HIII dummy in the simulations of the crashes used in this study.

Studying the results in Figures 6 to 9, one could expect that other parameters than mean and peak accelerations might influence injury risk. One of the occupants with symptoms more than one month was exposed to a low mean acceleration of 3.1 g, not likely to cause an AIS1 neck injury with long lasting symptoms. However, in that crash NIC_{max} was above 15 m^2/s^2, where the injury risk was found to be 20% in this study, while N_{km} was approximately 0.4, where the injury risk was below 5%.

It was shown that in crashes with resulting NIC_{max} of approximately 16 m^2/s^2, N_{km} varied between 0.4 and 1.6. Together with the statistical analysis showing relatively high positive predictive values and very high negative predictive values for both NIC_{max} and N_{km}, these facts indicate that both injury criteria separately influences injury risk. Therefore both criteria could be used to predict neck injury risk. A first attempt to combine these criteria was the MIX criteria. It was found to be useful to predict neck injury, but further studies should be conducted in this area.

Several studies have shown a higher AIS1 neck injury risk for females compared with males (Berglund 2002, Krafft 2002b, Langwieder et al. 2002, Otremski et al. 1989). It is important that critical levels for preventive measures are based on the most vulnerable occupants. Therefore risk curves should be calculated for males and females separately. Due to lack of data such risk curves could not be calculated in this study. However, in the results presented in Figures 6-11 both males and females are included, and from these figures critical levels can be identified taking both males and females into account.

CONCLUSIONS

Symptom duration of 110 occupants in rear impact crashes with three car models was compared with mathematical simulations with the BioRID II. The inclusion criterion was a recorded crash pulse (meaning a peak acceleration above about 3g). The only parameter that was varied in the simulations was the crash pulse and the seat. That is, the seat posture, head twisting, sex, psychosocial factors etc were not taken into account. Nevertheless, the NIC_{max} and the N_{km} values predicted a neck injury with initial symptoms or with symptom duration of more than one month with high accuracy. Also, risk curves were created. Injury risks for various neck injury criteria were found, which are useful for creating crash pulses and choosing injury criteria and tolerance levels.

It was found that simulated NIC_{max} and N_{km} values for a normal seated BioRID II exposed for rear impact crash pulses are applicable to predict risk of AIS1 neck injury. It is suggested that both BioRID II NIC_{max} and N_{km} should be considered in rear-impact test evaluation.

The findings in this study can be used to design car crash test specifications aimed at predicting risk of AIS1 neck injury.

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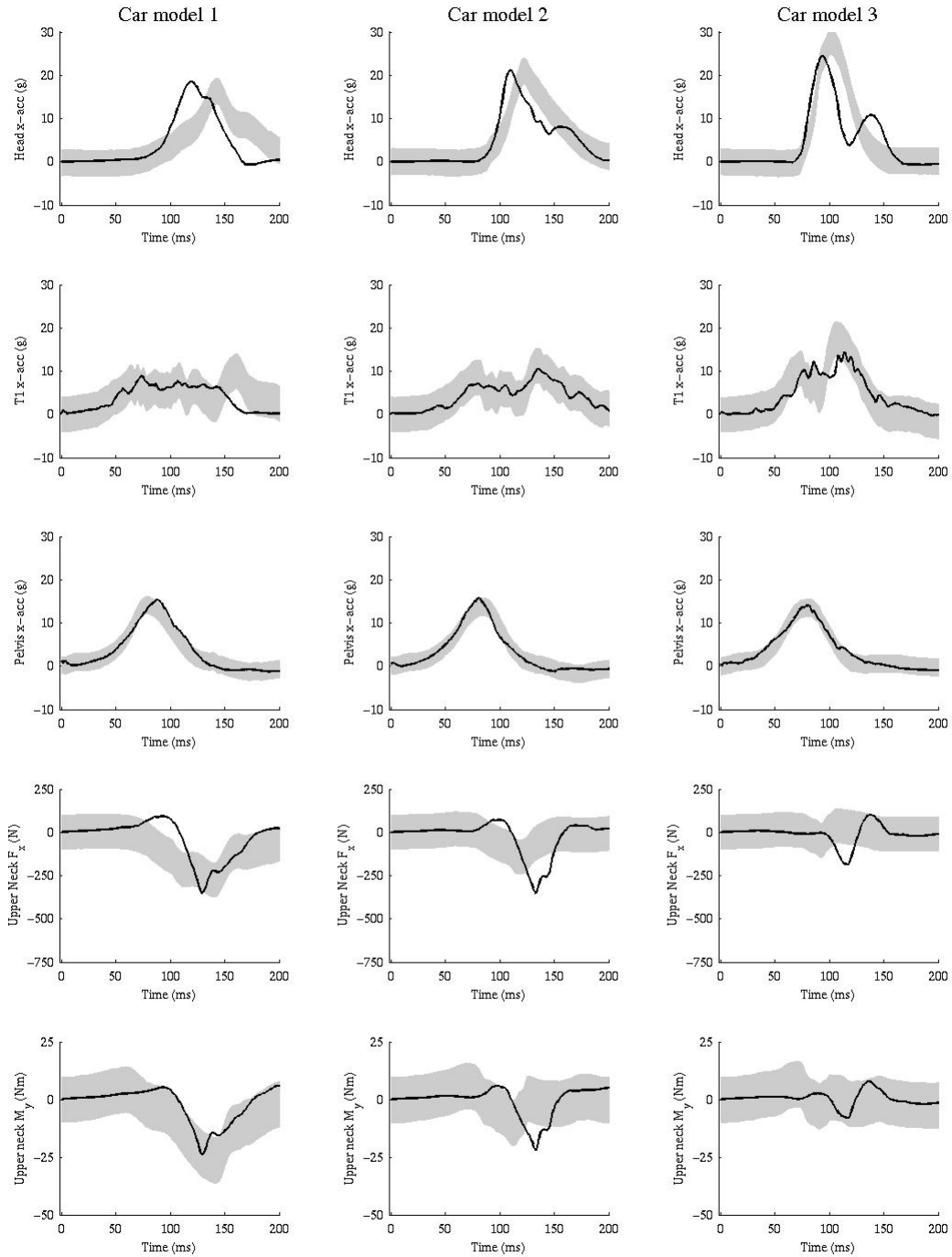
APPENDIX

Figure 18. Responses from tests with the BioRID II carried out at Δv 23 km/h and mean acceleration 4.5 g. Black lines are responses from Madymo simulations, gray areas are response corridors established from mechanical crash tests.